Bose-Einstein correlations at LEP

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BOSE-EINSTEIN CORRELATIONS AT LEP. *

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Bose-Einstein Correlations are studied since a long time in high energy physics, but are still poorly understood. As this effect can be a source of large systematic error in W mass measurement in the $WW \to q_1\bar{q}_2q_3\bar{q}_4$ channel, new studies are made by the four LEP experiments, both using the Z peak data (from LEP1)and the W pairs data (from LEP2). Also, looking at these correlations in W pair events gives an insight on the simultaneous hadronization of two color strings. The analyses performed by the four LEP collaborations are presented. In the $WW \to q_1\bar{q}_2q_3\bar{q}_4$ channel, a consistent picture of no correlations between the decay products of the two Ws seems to emerge.

1. Introduction

The existence of Bose-Einstein Correlations (BEC) between identical bosons in interactions producing hadronic final states is well established [1]. BEC leads to an enhancement of the two particle differential cross-section for pairs of identical pions close in phase space, i.e. occur at low values of $Q = \sqrt{(\mathbf{p_1} - \mathbf{p_2})^2 - (E_1 - E_2)^2}$. The correlation function is defined by $R_2(Q) = \rho_2(Q)/\rho_0(Q)$, where $\rho_2(Q)$ is the two pion density and $\rho_0(Q)$ is constructed from a sample identical to the like-charged pion pair sample, except for the presence of BEC.

2. Bose-Einstein Correlations in Z data

Z peak data have been recently analysed by DELPHI, L3 and OPAL, to search for a possible elongation of the pion source in Z decays [2]. The analyses use the longitudinal center-of-mass (LCMS) system defined for each pair of pions as the system in which the sum of the momenta of the pair is perpendicular to the thrust axis. In this system, the three-momentum

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difference of the pair can be expressed into a longitudinal component Q_L parallel to the thrust axis, Q_{out} along the sum of the pion's momenta and Q_{side} perpendicular to the (Q_L, Q_{out}) plane. Q_L and Q_{side} reflect spatial dimensions of the source, and Q_{out} is related to both spatial and temporal dimensions. The invariant four-momentum difference can be then written as $Q^2 = Q_L^2 + Q_{side}^2 + Q_{out}^2(1-\beta^2)$, where $\beta = (p_{out\ 1} + p_{out\ 2})/(E_1+E_2)$, with $p_{out\ i}$ and E_i (i=1,2) the out-component of the momentum and the energy of the particle i in the LCMS. The correlation function is parametrized as a function of $\vec{Q} = (Q_L, Q_{side}, Q_{out})$.
The reference sample, from which ρ_0 is determined, is formed either by mixing particles from different events (L3 and DELPHI), or is made of unlike-sign pion pairs (OPAL).
The mixing procedure introduces some biases which are estimated by Monte-Carlo using a generator without BEC, and the correlation function is corrected for. The effects of detector resolution, acceptance, efficiency and particle misidentification are also corrected for.
Concerning OPAL method, as Coulomb interactions affect differently like- and unlike-charged pairs, corrections based on Gamow factors, are applied. Distorsions caused by the reference sample (decays of hadron resonances and of weakly decaying particles) are taken into account using Monte-Carlo predictions. The correlation function for the data is divided by the same correlation function, obtained from the Monte-Carlo which does not include the BEC effect, to correct for residual distorsions.
The following three dimensional parametrizations are used:

$$\begin{aligned}
&(L3)\ R_2(Q_L, Q_{out}, Q_{side}) = \gamma(1 + \delta Q_L + \epsilon Q_{out} + \zeta Q_{side})\times \\
&\quad [1 + \lambda \exp(-R_L^2 Q_L^2 - R_{out}^2 Q_{out}^2 - R_{side}^2 Q_{side}^2 + 2\rho_{L,out} R_L R_{out} Q_L Q_{out})], \quad (1) \\
&(OPAL)\ R_2(Q_L, Q_{out}, Q_{side}) = \gamma(1 + \delta Q_L + \epsilon Q_{out} + \zeta Q_{side} + \delta' Q_L^2 + \epsilon' Q_{out}^2 + \zeta' Q_{side}^2) \\
&\qquad \times [1 + \lambda \exp(-R_L^2 Q_L^2 - R_{out}^2 Q_{out}^2 - R_{side}^2 Q_{side}^2)], \quad (2)
\end{aligned}$$

where the factor $(1 + \delta Q_L + \epsilon Q_{out} + \zeta Q_{side} + ...)$ takes into account possible long-range correlations and γ is a normalization factor. The second term parametrizes the BEC, λ being the strenght of the effect and the radius R_i being related to the size of the pion source in the i coordinate.
In L3 analysis, the off-diagonal term $\rho_{L,out} R_L R_{out}$ is found consistent with zero, and is fixed to this value. Other parametrizations are also used: the Gaussian fit is replaced either by an Edgeworth expansion or by an exponential fit. All the results are compatible with a non-spherically symmetric source, the longitudinal radius being found larger than the transverse radius: $(R_{side}/R_L)_{Gauss.} = 0.80 \pm 0.02\ (stat)^{+0.03}_{-0.18}\ (syst)$. From the OPAL fit, the longitudinal radius is also found to be larger than the transverse radius: $(R_L/R_{t,side}) = 1.222 \pm 0.027\ (stat)^{+0.075}_{-0.012}\ (syst)$. DELPHI makes a

two dimensional analysis, where the transverse component Q_T is defined as $Q_T = \sqrt{Q_{side}^2 + Q_{out}^2}$. The following two dimensional parametrization is used: $R_2(Q_L, Q_T) = \gamma \times [1 + \lambda \exp(-R_L^2 Q_L^2 - R_T^2 Q_T^2)]$. The following fitted values are obtained: $R_L = 0.53 \pm 0.02$ $(stat) \pm 0.07$ $(syst)$ fm and $R_T = 0.85 \pm 0.02$ $(stat) \pm 0.07$ $(syst)$ fm, in good agreement with L3 and OPAL results.

Thus, three LEP collaborations have analysed Z data, and shown that the pion source is elongated along the event axis direction. This feature is not simulated by the JETSET Monte-Carlo. This generator includes a very simple algorithm for the BEC simulation, which does not distinguish between the longitudinal and tranverse components of the correlation radius.

2.1. Bose-Einstein Correlations in W pair data

2.2. ALEPH *analysis*

The ALEPH experiment has analysed the data recorded at center-of-mass energies from 172 to 202 GeV using the unlike-sign pairs as a reference sample. A model (JETSET BE_3 [3]) of BEC is adjusted on the data recorded at 91 GeV at the Z peak. The parameters of this model have been adjusted to $\lambda = 2.3$ for the magnitude of the effect and $R = 1/\sigma$=0.26 GeV for the source size. A b-tagging algorithm is used to select $Z \to b\bar{b}$ events, allowing to measure BEC in b flavor and in u, d, s, c flavors at the Z peak separately. Residual discrepancies between data and Monte-Carlo for u, d, s, c flavors are corrected bin by bin. The prediction of this model tuned and corrected at the Z peak is in good agreement with the data in the $W^+W^- \to q_1\bar{q}_2 l\nu_l$ events. In the $WW \to q_1\bar{q}_2 q_3\bar{q}_4$ channel, Monte-Carlo prediction with BEC between decay products of the two Ws is disfavored at the level of 2.2 standard deviations [4].

2.3. OPAL *analysis*

The OPAL collaboration has analysed the data recorded at 172, 183 and 189 GeV center-of-mass energies. The correlation function in the $WW \to q_1\bar{q}_2 q_3\bar{q}_4$ channel is written as the sum of the contribution from each $W \to q_1\bar{q}_2$ decay, from BEC between the two Ws, and from BEC in the $Z, \gamma^* \to q\bar{q}$ background. The correlation function for $WW \to q_1\bar{q}_2 l\nu_l$ and Z, γ^* background are written in the same way, and the three correlation functions are then fitted simultaneously. The values obtained for W and Z are similar, and the values obtained for BEC between the two Ws are $\lambda = 0.05 \pm 0.67$ $(stat.) \pm 0.35$ $(syst.)$ and $R = 1.51 \pm 0.05$ $(stat.) \pm 0.09$ $(syst.)$ fm. This result is compatible with no BEC between the Ws, but the error is too large to allow any strong conclusion [5].

2.4. Common LEP *analysis*

Two years ago, LEP conclusion was unclear as DELPHI and ALEPH collaborations reached opposite conclusions. The LEP collaborations thus acknowledged one method to analyze this effect, first proposed in [6]. The method is based on the observables:

$$\Delta\rho(Q) = \rho_2^{WW}(Q) - 2\rho_2^{W}(Q) - 2\rho_{mix}^{W^+W^-}(Q), \quad (3)$$

$$D(Q) = \frac{\rho_2^{WW}(Q)}{2\rho_2^{W}(Q) + 2\rho_{mix}^{W^+W^-}(Q)} \quad (4)$$

where ρ_2^{WW} is the two pions density in fully hadronic W events, ρ_2^{W} the two pions density in $WW \to q_1\bar{q}_2 l\nu$ events and $\rho_{mix}^{W^+W^-}$ the product of the single particle density, constructed by pairing particles originating from two different $WW \to q_1\bar{q}_2 l\nu$ events. $\Delta\rho(Q)$ must be equal to 0 if there are no correlations between W decay products, and $D(Q)$ must be equal to 1. The distribution $D(Q)$ is divided by the same distribution obtained for Monte-Carlo without BEC, to correct for distorsions due to event mixing, non-BEC correlations and possible detector effect: $D'(Q) = D(Q)_{data}/D(Q)_{MC\ no\ BEC}$. J is the integral of the $\Delta\rho(Q)$ distribution from 0 to 0.68 GeV (L3) or 1 GeV (DELPHI). The $D(Q)$ distribution is fitted with $(1+\epsilon Q)(1+\Lambda exp(-k^2Q^2))$ (L3) or with $(1+\epsilon Q)(1+\Lambda exp(-kQ))$ (DELPHI) where Λ gives the strenght of the (hypothetic) BEC between the Ws. L3 and DELPHI have analyzed their data [7] from 189 to 209 GeV center-of-mass energies, and obtained: $J_{L3} = 0.02 \pm 0.33$ $(stat.) \pm 0.24$ $(syst.)$, $\Lambda_{L3} = 0.008 \pm 0.018$ $(stat.)$ $\pm$ 0.016 $(syst.)$ (see also fig. 1 to 4) and $J_{DELPHI} = 0.012 \pm 0.015$, $\Lambda_{DELPHI} = -0.037 \pm 0.055$ $(stat.)$ ± 0.055 $(syst.)$ in agreement with the hypothesis of no BEC between the two Ws. Monte-Carlo predictions, with BEC between the two Ws, give $J = 0.052 \pm 0.006$ and $\Lambda = 0.24 \pm 0.03$ (DELPHI). Preliminary results from ALEPH are in qualitative agreement [8].

3. Conclusion

BEC are measured using the high statistics of LEP1 data, and it is shown that the source is elongated along the event axis and not spherically symmetric. This result must be taken into account in future BEC models. BEC are measured in W pair decays: conclusions obtained by ALEPH, DELPHI and L3 are in favor of no correlations between the pions from different Ws in the $WW \to q_1\bar{q}_2 q_3\bar{q}_4$ channel. OPAL result is also compatible with

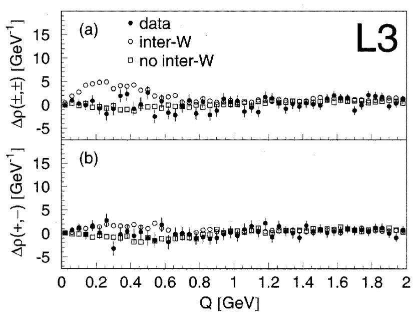

Fig. 1. $\Delta\rho(Q)$ distributions for like- and unlike-charged pion pairs. L3 data are compared to MC predictions without (no inter-W) and with (inter-W) BEC between decay products of the two Ws.

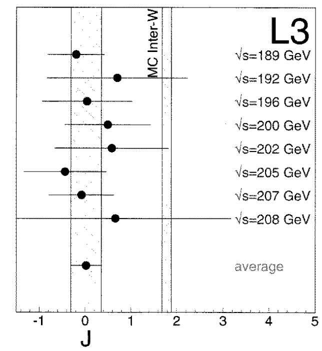

Fig. 2. Results of the integration of the $\Delta\rho(Q)$ distribution up to 0.68 GeV, at different center-of-mass energies. The average is compared to Monte-Carlo prediction with BEC between the two Ws.

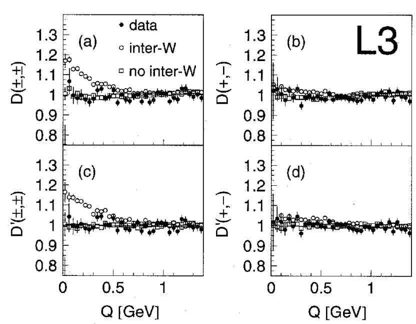

Fig. 3. $D(Q)$ and $D'(Q)$ distributions for like- and unlike-charged pion pairs. L3 data are compared to MC prediction without (no inter-W) and with (inter-W) BEC between decay products of the two Ws.

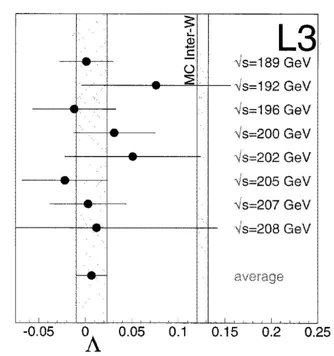

Fig. 4. Results of the fit of the $D'(Q)$ distribution, at different center-of-mass energies. The average is compared to MC prediction with BEC between the two Ws.

no correlations between the two Ws, but suffers from a large uncertainty. The abscence of BEC between pions from different Ws in the fully hadronic channel can be expected from the Lund string model, where the correlation

between **x** and **p** is large [9], the production being thus coherent. This is also supported by the measurement of the BEC in two and three jets events at Z done by DELPHI and by the measurement of the two neutral pions correlation done by L3[10]. But there are still some questions, as the preliminary genuine three-charged particle correlation measurement from L3 is more in favor of incoherent production [11].
The actual uncertainty on the LEP W mass is ± 26 (*stat.*) ± 30 (*syst.*) MeV. The measurement in the four quark channel gives 80.457 ± 0.062 GeV, where the error is still dominated by color reconnection (40 MeV) and BEC (25 MeV), responsible for the low weight of this channel in the combination. The combination of the other channels gives 80.448 ± 0.043 GeV. The similarity of these two measurements can also be interpreted as an indication of small final state interactions in the fully hadronic channel.

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